FEATURE

Mexico's Long-Term Energy Outlook

Results of a Detailed Energy Supply and Demand Simulation

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This paper presents the results of a detailed, bottom-up analysis of Mexico's energy markets. A team of U.S. and Mexican analysts used the Energy and Power Evaluation Program (ENPEP) to develop energy market forecasts to the year 2025. Primary energy supply is projected to grow from 9,313 petajoules (PJ) in 1999 to 13,130 PJ by 2025. Mexico's crude oil production is expected to increase by 1% annually to 8,230 PJ in 2025. As its domestic crude refining capacity becomes unable to meet the rising demand for petroleum products, resulting from such factors as the country's rapidly growing transportation needs, imports of oil products will become increasingly important. Gasoline imports, for example, are expected to increase 12-fold. The Mexican natural gas markets are driven by the strong demand for gas in the power generating and manufacturing industries. This demand is expected to significantly outpace projected domestic production. The result will be a large demand for natural gas imports, perhaps representing approximately 46% of total gas supplies by 2025. The long-term market outlook for Mexico's electricity industry shows a heavy reliance on natural-gas-based generating technologies. Gas-fired generation is forecast to increase 26-fold, eventually accounting for 79% of total generation by 2025. Alternative results for a constrained-gas scenario show a substantial shift to coal-based generation and the associated effects on the natural gas market.

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Introduction

Under a Technical Cooperation (TC) project initiated in June 2000 and funded by the International Atomic Energy Agency (IAEA) and the U.S. Department of State, a team of analysts from the Secretaría de Energía (SENER), Comisión Federal de Electricidad (CFE), Instituto de Investigaciones Eléctricas (IIE), the Dirección General de Servicios de Cómputo Académico (DGSCA), the Programa Universitario de Energía (PUE), and the Facultad de Ingeniería, all three at the Universidad Nacional Autónoma de México (UNAM), and the Center for Energy, Environmental, and Economic Systems Analysis (CEEESA) in the Decision and Information Sciences Division at Argonne National Laboratory finished a detailed analysis of Mexico's power sector that evaluated various power system expansion options and scenarios.

In September 2001, the scope of the analysis was broadened into a full energy system analysis that analyzed Mexico's future energy needs up to 2025 and estimated the associated environmental burdens. The previous team of analysts was joined by experts from the Instituto Nacional de Ecología (INE), Instituto Mexicano del Petróleo (IMP), Petróleos Mexicanos (PEMEX), and the Comisión Nacional para el Ahorro de Energía (CONAE). Final results were presented at a seminar at SENER in February 2003.

Modeling Approach

Under Phase 1 — the power system expansion analysis — the team used primarily the DECADES-WASP and VALORAGUA analysis tools. WASP is a dynamic optimization software that determines the optimal, least-cost generation system expansion path that adequately meets the growing demand for electricity while respecting user-specified constraints, such as desired system reliability, fuel limitations, or environmental constraints. WASP uses a probabilistic simulation of production costs, energy-not-served costs, and system reliability parameters to compare total costs of alternative expansion paths.

VALORAGUA determines the optimal generating strategy of mixed hydro-thermal electric power systems. It can simulate the operation of all forms of hydropower plants (run-of-river, weekly, monthly, seasonal, or multi-annual regulation), including pumped-storage plants and multipurpose hydro projects. Both models have been in use at CFE for several years.

For the overall energy systems analysis under Phase 2, the team added the BALANCE module of ENPEP for Windows. BALANCE uses a nonlinear, market-based equilibrium approach to determine the energy supply and demand balance for the entire energy system. With this approach, BALANCE is used to determine the response of various segments of the energy system to changes in energy price and demand levels. The model relies on a decentralized decision-making process in the energy sector and can be calibrated to the different preferences of energy users and suppliers. Basic input parameters include information on the energy system structure; base-year energy statistics, including production and consumption levels and prices; projected energy demand growth; and any technical and policy constraints.

Energy and electricity demand growth rates were estimated using the MODEMA model, which includes 3 resource supply sectors, 9 conversion and distribution sectors, and 26 demand sectors. The modeling framework and information flows are shown in Figure 1.

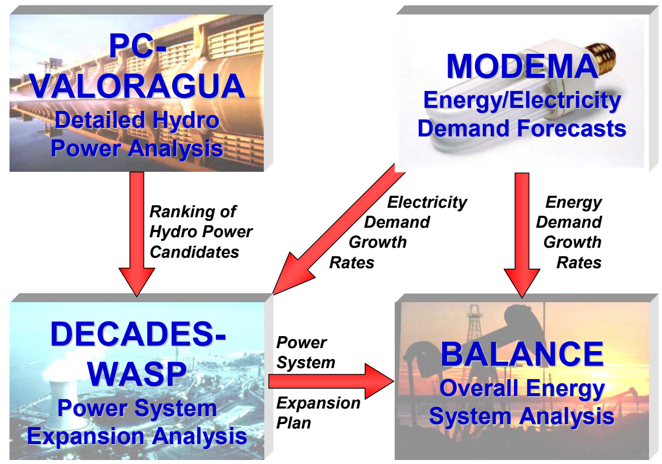

Figure 1: Modeling Framework, Information Flow

Energy System Representation

The BALANCE model uses a graphical representation of the energy system, a so-called energy network, that is designed to trace the flow of all energy forms from primary resource level to final or useful energy demand, that is, transportation gasoline, residential hot water, or industrial process steam. The Mexican analysts used the BALANCE windows interface controls to develop the Mexican energy system representation on-screen.

Figure 2 displays the general energy network representation, showing all the economic sectors included in the analysis. In addition to the basic resource supply sectors, the network includes several conversion and distribution sectors as well as multiple demand sectors. Industry is divided into 17 individual industrial branches. Each sector is developed at a different level of detail, depending on data availability and analytical needs. An initial attempt was made to configure the model at the regional level, but lack of regional information, particularly demand-side data but also oil and gas sector data, made it necessary to adopt a national-level

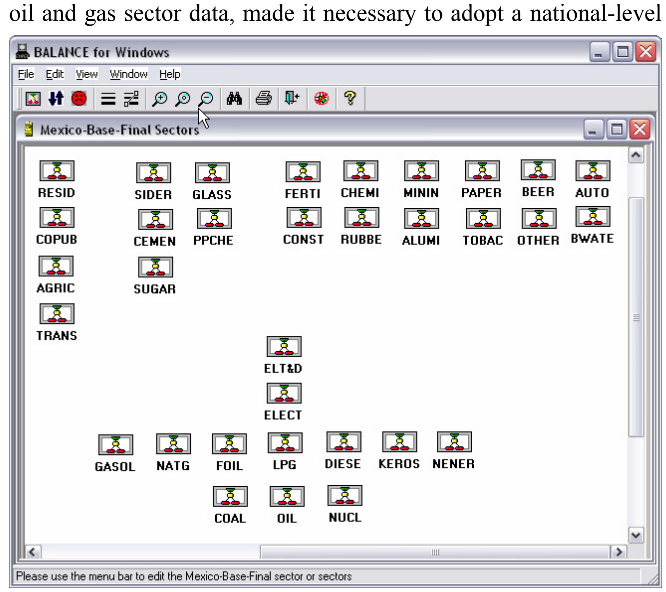

Figure 2: ENPEP Network for Mexico

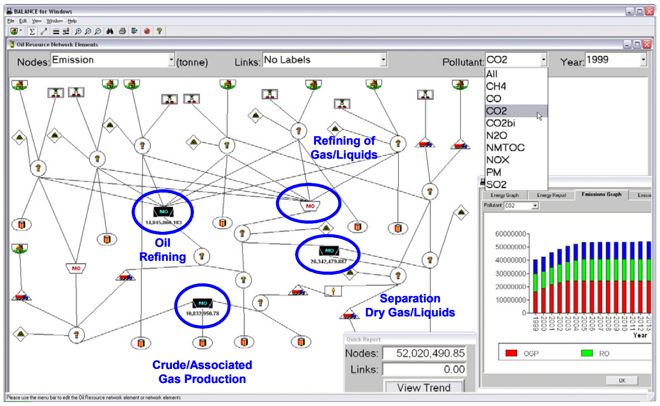

Figure 3: Oil and Gas Sector Representation

implementation. SENER is in the process of collecting a comprehensive set of regional data that could be used in a future, updated model configuration.

Figure 3 presents the oil and gas sector implementation. After associated natural gas is separated, crude oil is processed in the oil refining step into the different petroleum fuels, such as gasoline and diesel. Wet gas and wet associated gas moves through the gas processing plants to remove natural gas liquids. Gas liquids are processed into oil products in a subsequent step. Dry natural gas and gas imports are sent directly for distribution to the final consumers. Also included in the sector is the "maquila" process whereby Mexico sends crude oil to foreign refineries and receives back petroleum products, primarily gasoline and diesel.

Mexico's power system is generally divided into nine generation regions, six of them interconnected and three isolated (Baja California, Baja California Sur, and the Northwest Region). In 1999, the interconnected system accounted for 85% of installed capacity and 88% of generation and was modeled in detail at the unit level. For convenience, individual units were assembled into different fuel groups; in the case of Mexico, the team decided on nine thermal groups and one hydro group. The top of Figure 4 shows the interconnected system with the fuel groups and unit details for two groups (hydro and fuel oil). Less detailed information was available for the isolated grid. Therefore, the isolated system was modeled with a simpler, more aggregated approach. The isolated grid is shown in the bottom part of Figure 4. Non-dispatchable renewables are also included in this network sector.

The network includes several transmission and distribution (T&D) sectors, particularly for the various petroleum products. The T&D sectors incorporate distribution costs (if available) and government taxes and subsidies (if applicable), with the model computing the end-use energy prices across the different sectors to send the correct price signals to consumers. Figure 5 shows an example for the diesel distribution network. Figure 5 also presents the sugar industry as an example for an end-use sector. Various furnaces, boilers, and cogenerators compete to supply the sugar industry's demand for direct heat and process steam. Cogeneration offers an alternative supply to grid-purchased electricity.

Scenarios and Main Assumptions

For the power sector, the analysts examined a total of 14 scenarios, including a base case, variations in load growth, sensitivities to changes in projected fuel prices, variations in assumed natural gas

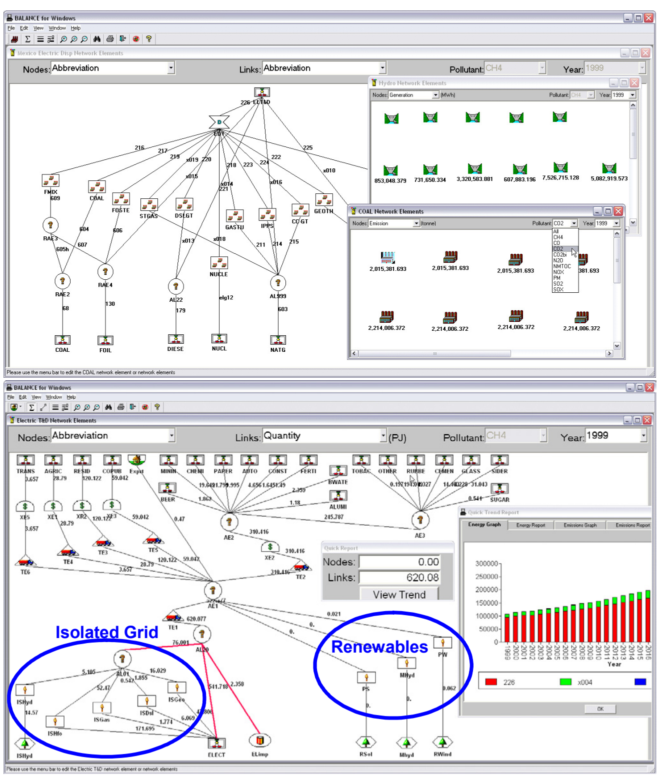

Figure 4: Electric Sector Representation

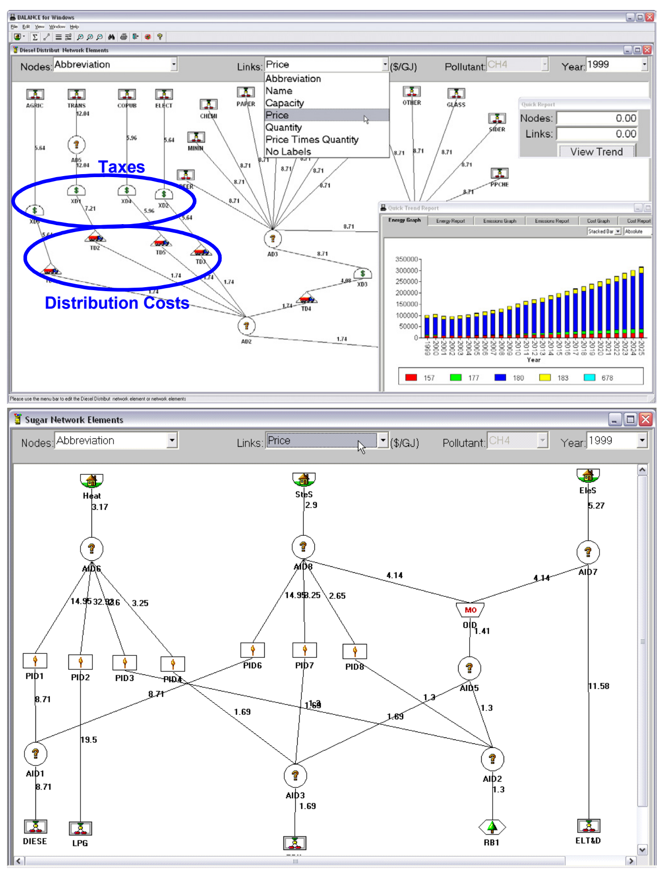

Figure 5: T&D and End-Use Sector Representation

availability, different system reliability targets, and the possibility for additional nuclear capacity. The power sector analysis is described in more detail in Conzelmann et al. (2003). Forecasts until 2025 for the entire energy system were developed for the following four scenarios:

- Reference Case;
- Limited Gas Scenario – assumes limited gas supply for power generation starting in 2009 (maximum addition of 3 combined cycle units per year);
- Renewables Scenario – investigates impacts of additional renewables for power generation (primarily wind plus some solar-photovoltaic);
- Nuclear Scenario – analyzes the impacts of additional nuclear power generation capacity.

The analysis period for all scenarios was 1999 to 2025, with the first 3 years used to calibrate the ENPEP-BALANCE model to the Mexican situation. Economic growth was assumed to be 4.5% from 2002 through 2011 and 3.5% from 2012 through 2025. Assumed population growth rates drop from 1.33% (2000-2010) to 1.02% (2011-2020) and 0.82% for the remainder. Fuel price escalation rates were developed based on Bates (2002), who estimated fuel price indexes using information from the World Bank and USEIA. The discount rate was set at 10% in all scenarios. No constraints were imposed on the supply of natural gas under the Reference Case.

Reference Case Results – Final Energy Consumption

Final energy consumption is projected to grow at an average rate of 3.8% per year, from 4,030 PJ in 1999 to 10,666 PJ by 2025 (Figure 6). This growth is strongly fueled by the observed increase in transportation demand, which is projected to grow annually at 4.9% from 1,547 PJ in 1999 to 5,349 PJ in 2025. Transportation accounts for about 57% of the total growth in final consumption (6,636 PJ), making the transport sector the largest consumer by 2025 with over 50% of total final energy consumption (up from 38% in 1999). Industrial demand grows at 3.8% per year, leading to a slight decline in its consumption share from 39% to 37%. By 2025, transport and industry combined account for about 88% of total final energy consumption. Residential energy consumption grows relatively slowly at about 1% annually, leading to a drop in its sectoral share from 17% (1999) to 8% (2025).

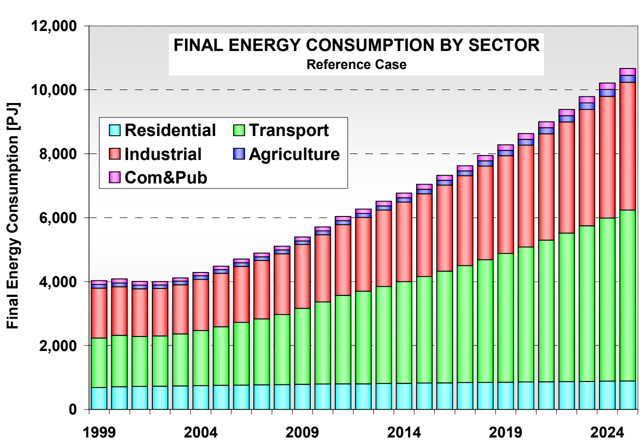

Figure 6: Reference Case Final Energy Consumption by Sector

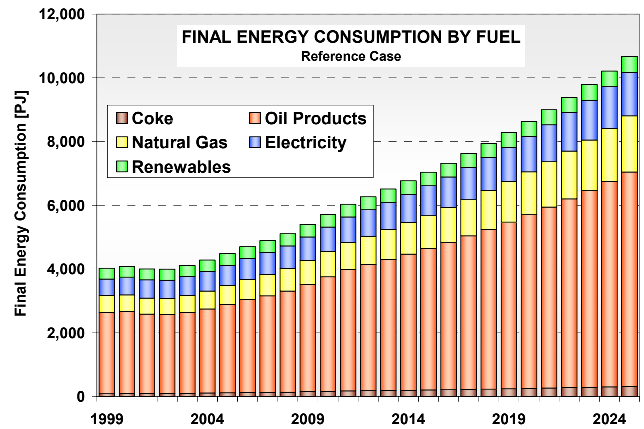

Figure 7: Reference Case Final Energy Consumption by Fuel

As Figure 7 shows, the model projects refined oil products to continue to play a dominant role in Mexico's energy future. The share of oil products will remain at approximately 63% throughout the forecast period. Final natural gas consumption grows from 527 PJ to 1,764 PJ (4.8% annually), with the industrial sector accounting for about 90% of the total growth, or 1,114 PJ.

The results for the manufacturing sector are displayed in Figure 8. Projections show industrial energy requirements growing from the current 1,561 PJ (1999) to 3,992 PJ (2025). While fuel oil consumption actually declines from 203 PJ in 1999 to 79 PJ in 2025, consumption of other fuels increases, particularly natural gas, which is forecast to continue its penetration of the industrial market. Industrial gas consumption is expected to more than triple from about 500 PJ to 1,615 PJ. Industrial electricity demand is projected to be equally strong, also tripling from 310 PJ to 986 PJ over the forecast period.

The strong growth in transportation energy demand from 1,547 PJ to 5,349 PJ is shown in Figure 9. Motor gasoline and diesel combined will continue to provide 90% of the total transport energy needs, with gasoline accounting for about 63%. Market shares of transportation fuels are forecast to change very little.

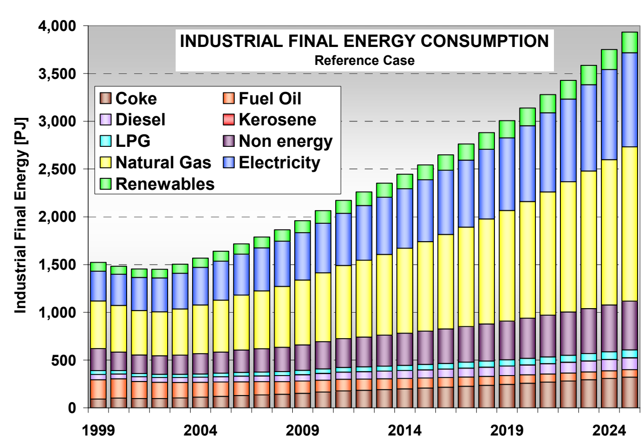

Figure 8: Reference Case Industrial Final Energy Consumption by Fuel

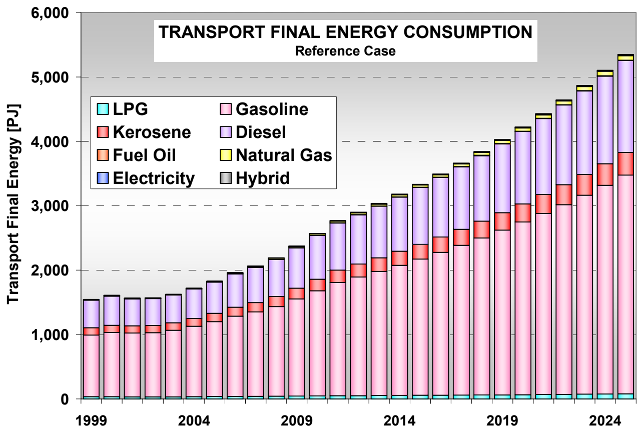

Figure 9: Reference Case Transportation Final Energy Consumption by Fuel

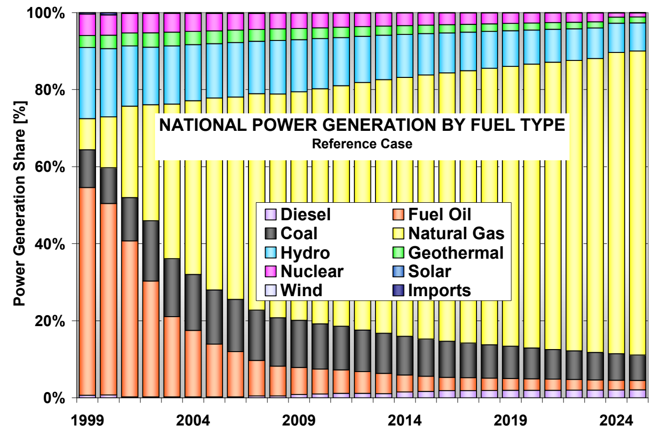

Figure 11: Reference Case Power Generation Share by Fuel Type

Reference Case Results – Power Sector

Mexico's power sector is expected to undergo significant changes over the forecast period. Model results show a dramatically increasing reliance on natural gas for future system expansion as shown in Figure 10 and Figure 11. While Mexico's fuel oil units are either retired or converted to imported coal, natural gas-fired generation increases more than 25 times by 2025. As a result of this development, fuel oil generation decreases from 333 PJ or 92 terawatt-hours (TWh) in 1999 to 39 PJ (11 TWh) in 2025, a drop of 88%. Coal generation slightly increases in the early years from 61 PJ (17 TWh) in 1999 to 106 PJ (29 TWh) in 2002 and remains at this level throughout the projection period.

Natural gas generation grows at an average rate of 13.2%, from 50 PJ (14 TWh) in 1999 to 1,265 PJ (351 TWh) in 2025. By the end of the projection period, gas-fired generation accounts for 79% of total generation (up from 8% in 1999). Hydro and other renewables grow only modestly, leading to a gradual decline in their market share from 22% in 1999 to about 9% in 2025. More details on Mexico's power sector projections are provided by Conzelmann et al. (2003).

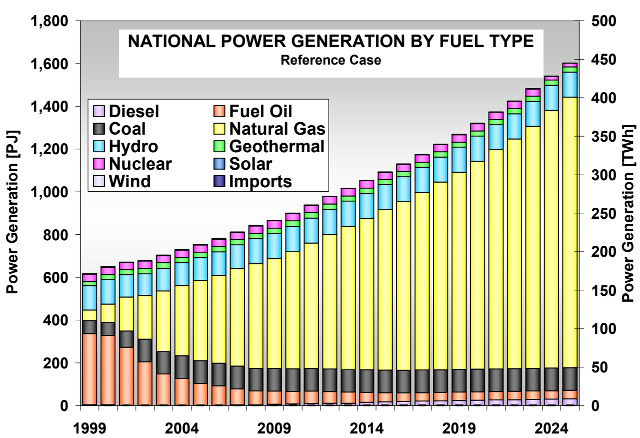

Figure 10: Reference Case Power Generation by Fuel Type

Reference Case Results – Oil and Gas Supply

Given the strong growth in transport gasoline demand, Mexico's five refineries are expected to run into their combined capacity limits around 2005. This situation drives up the need for gasoline imports from 196 PJ (1999) to 2,276 PJ (2025), a 12-fold increase equivalent to an annual growth of 9.9%. By 2025, imports supply 66% of Mexico's gasoline consumption, up from 20% in 1999.

Projected net imports of refined petroleum products are shown in Figure 12. Net imports of refined oil products quickly increase from 215 PJ (1999) to 3,749 PJ (2025). By 2025, net gasoline imports amount to 2,063 PJ, or 55% of total net oil product imports. Net diesel imports are forecast to be 1,098 PJ, or 29% of total net oil product imports.

Figure 13 shows Mexico's net oil export balance. The graph clearly shows the impact of the projected growth in refined product imports. While crude oil exports are expected to continue their growth at an average rate of 0.7% per year from 3,396 PJ in 1999 to 4,520 PJ in 2025, net imports of refined products quickly increase and result in a rapid drop in net oil exports, eventually declining to 771 PJ in 2025, down from a peak of 3,848 PJ in 2005.

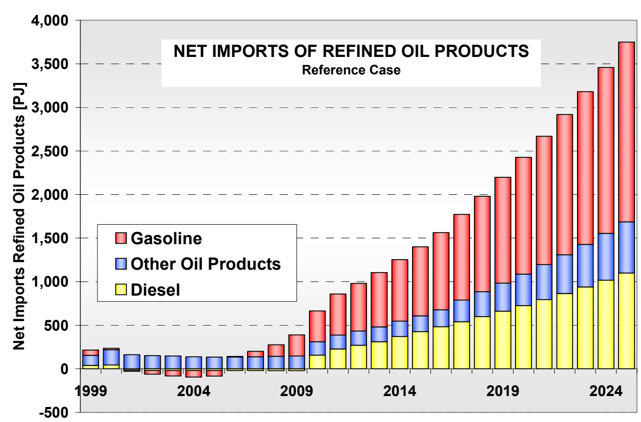

Figure 12: Reference Case Net Imports of Refined Oil Products

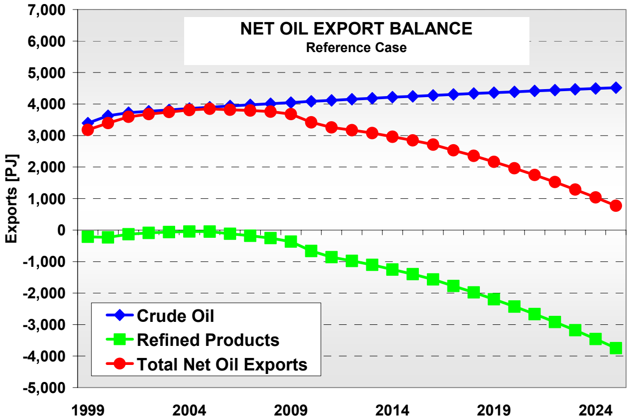

Figure 13: Reference Case Net Oil Export Balance

Total natural gas demand is forecast to grow from 799 PJ (21 billion m^3) to 4,678 PJ (127 billion m^3) over the projection period (Figure 14). Despite the strong growth in industrial demand (1,114 PJ total growth, or 4.6% per year), the growth in natural gas demand is heavily driven by the power sector dynamics. Natural gas consumption for power generation quickly grows from 273 PJ (7 billion m^3) in 1999 to 2,914 PJ (79 billion m^3) in 2025, equivalent to a 9.5% annual growth rate and accounting for 68% (2,641 PJ) of the total growth.

Natural gas supply model results are shown in Figure 15. The rapidly growing demand is expected to put a strain on the domestic gas supply system. Results indicate the need to develop additional gas fields or rely on increasing gas imports, particularly after 2008 when gas fields currently under development reach their maximum output (domestic non-associated gas). At the same time, associated gas production is projected to slow down as Mexico's oil refineries reach their combined process capacity, limiting domestic crude oil production (assuming export markets cannot absorb this incremental production). The results are clearly driven by some of the oil and gas sector-specific assumptions, such as (1) total capacity of all gas processing plants remains constant at 5.034 billion ft^3 per day, (2) total capacity of all fractionating plants remains constant at 544 million ft^3 per day, (3) natural gas exports

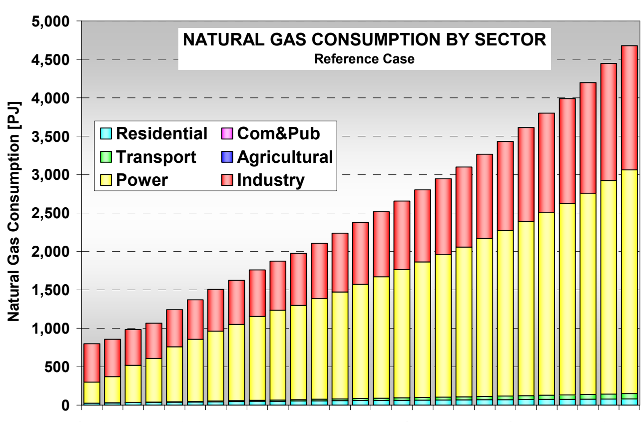

Figure 14: Reference Case Total Projected Natural Gas Demand by Sector

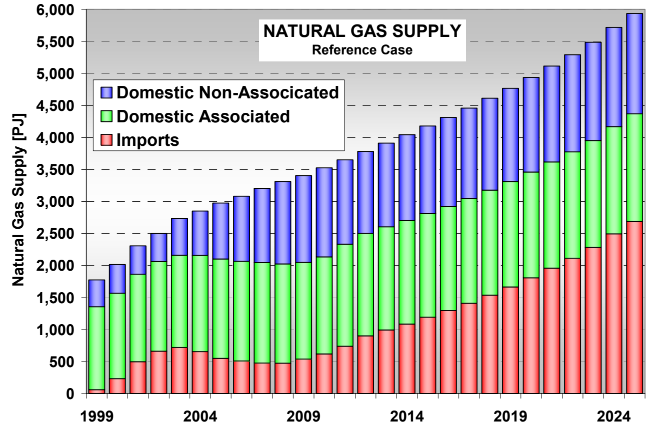

Figure 15: Reference Case Natural Gas Consumption by Sector

are marginal and decreasing, and (4) the ratio of crude to associated gas remains constant at the historical level.

It should be noted that according to SENER's most recent natural gas market analysis (SENER, 2002), PEMEX may substantially increase its natural gas investment program, with the goal of increasing its gas processing capacity, adding new integrated gas processing plants in the Burgos region, expanding its existing fractionating facilities in Coatzacoalcos, and upgrading its pipeline system. Under the accelerated gas development program, domestic natural gas production may increase substantially to almost 9.0 billion ft^3 per day by 2010 and thereby significantly alter the results above. This issue may be analyzed in more detail in subsequent model runs.

In addition, the study reported here did not attempt to investigate different sources of imported gas or whether it will be in the form of liquefied natural gas (LNG) and where these LNG terminals will likely be located. Undoubtedly though, if Mexico will not be able to close the projected gap between supply and demand either from additional domestic supplies or new imports, it might be exposed to price volatility similar to what has been observed in the United States recently where, according to Alan Greenspan (2003), "futures markets anticipate that the current shortage in natural gas will persist well into the future."

Reference Case Results – Atmospheric Emissions

Carbon dioxide (CO_2) emissions are forecast to grow at an average annual rate of 3.4% from 346 million metric tons (mt) in 1999 to 828 mt in 2025 (Figure 16). Transportation-related emissions grow the fastest at 4.9% per year from 108 mt to 371 mt over the forecast period, accounting for 55% of the total growth in CO_2 emissions. By 2025, the transport sector is responsible for 45% of Mexico's CO_2 emissions (up from 31% in 1999), followed by the power sector with 193 mt and 23% (up from 98 mt and 28%) and industry with 147 mt and 18% (up from 58 mt and 17%). The 5% drop in the power sector share is related to the rapidly growing penetration of natural gas as an energy source in that sector.

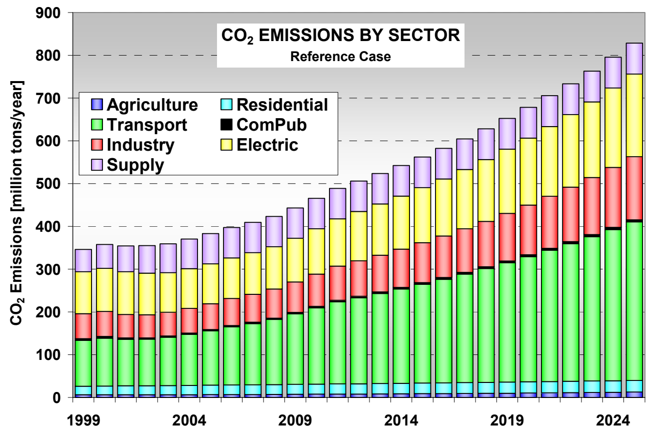

Figure 16: Reference Case CO_2 Emissions by Sector

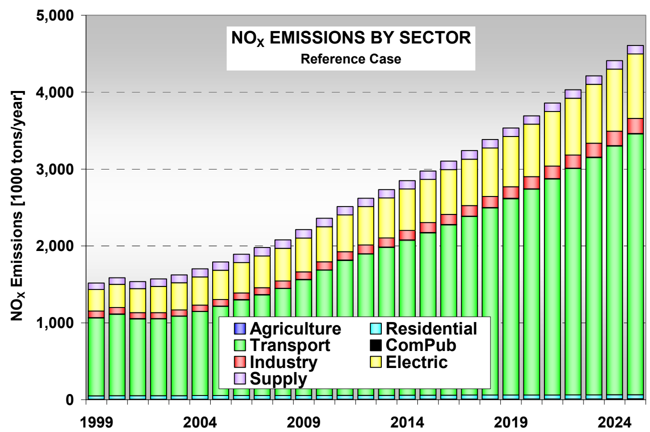

Figure 17: Reference Case NO_X Emissions by Sector

As shown in Figure 17, national emissions of nitrogen oxides (NO_X) are projected to increase from 1.52 mt (1999) to 4.61 mt (2025), equivalent to a 4.4% growth rate. This development is closely linked to transport sector dynamics, as the sector contributes about 77%, or 2.38 mt, to the overall growth in NO_X emissions. The transport share remains very high and gradually increases from 67% to 74% through the forecast period. The power sector, the second largest source, contributes 282 kilotons (kt) or about 19% in 1999 and 837 kt or about 18% in 2025.

Figure 18 presents the projected sulfur dioxide (SO_2) emissions, which exhibit a marked reduction of about 24% from 1999 to 2025. Emissions are forecast to initially decline from 2.35 mt (1999) to a low of 1.21 mt (2008) and then gradually increase again to 1.78 mt (2025). The most notable change is the substantial drop in power sector emissions from 1.71 mt (73% of the total) in 1999 to 0.38 mt (22% of the total) in 2025. This drop is linked to the retirement of several of Mexico's fuel oil units burning high-sulfur fuel oil, the conversion of some of the fuel oil units to low-sulfur imported coal plants, and the projected dramatic switch to natural gas for power generation with essentially zero SO_2 emissions.

The gradual increase in national SO_2 emissions after 2008 is related to the rise in industrial SO_2 emissions, which grow on average at about 3.4% from 0.44 mt in 1999 to 1.07 mt in 2025 as the sector

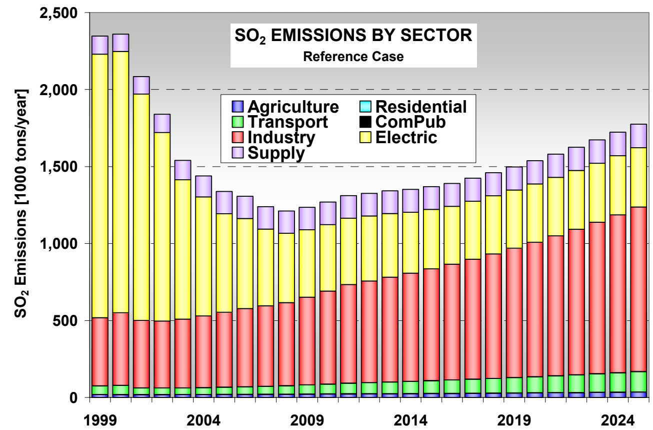

Figure 18: Reference Case SO_2 Emissions by Sector

continues to burn high-sulfur fuel oil. This situation causes the manufacturing sector to become the largest source of SO_2 by the end of the analysis period, contributing 60% of SO_2 emissions as compared to 19% in 1999.

Projected emissions of particulate matter (PM) are given in Figure 19. The behavior of PM emissions is somewhat comparable with the previous discussion for SO_2 in that emissions initially decline

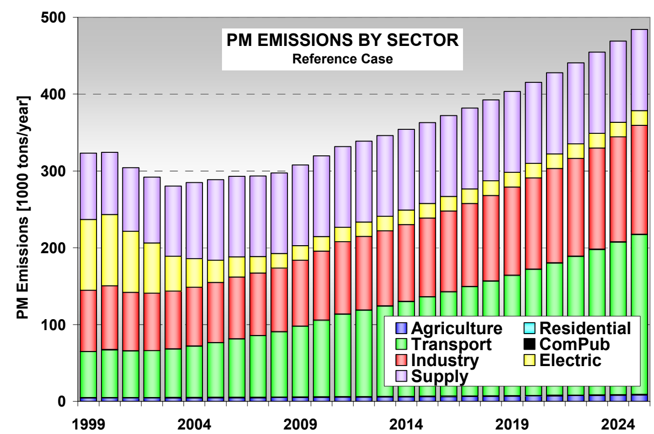

Figure 19: Reference Case PM Emissions by Sector

from 323 kt (1999) to 280 kt (2003) and then increase to 484 kt (2025). However, the drop in power-sector PM emissions is not nearly enough to offset the continued emissions growth in the other sectors, therefore leading to an overall increase in PM emissions. While power sector PM emissions decline from 92 kt (29% of total, largest PM source) in 1999 to 19 kt (4% of total) in 2025, emissions in other sectors, particularly the transport and industrial sectors, continue to grow. By 2025, transportation is the largest PM source, with 208 kt or 43% of the total (up from 60 kt or 18% of the total in 1999).

Alternative Scenario Results – Limited Gas Supply

The limitation of the gas supply for power generation changes the expected expansion of the power sector substantially. Starting in

2009, the expansion model selects the maximum of three combined cycle units each year instead of three to seven units per year under the Reference Case. The cumulative number of combined cycle units under the Limited Gas Scenario is 85 or 44.8 gigawatts (GW) as compared to 118 units (62.2 GW) under the Reference Case.

The effect on generation by fuel type can be seen in Figure 20. It is noteworthy that while the gas limitation becomes effective in 2009, the generation results do not show a significant difference until 2014, the year when WASP/DECADES projects the first coal-fired units to come on-line. During 2009 to 2013, even though there are four combined cycle units less than in the Reference Case, new coal units are not needed until 2014. Starting in 2014, the model projects between four and six coal-fired units to come on-line each year, with a total of 57 coal units or 17.7 GW. Correspondingly, coal generation starts to increase quickly from 106 PJ (29 TWh) in 2013 to 572 PJ (159 TWh) by 2025, accounting for 36% of total power generation. The increased coal generation essentially replaces up to 470 PJ of gas-fired generation by 2025 (Figure 21). The share of natural gas generation, therefore, reaches only about 50%, compared to 79% under the Reference Case.

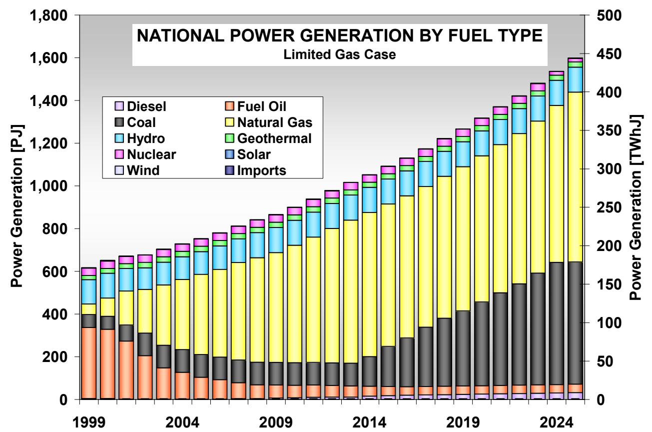

Figure 20: Limited Gas Scenario Power Generation by Fuel Type

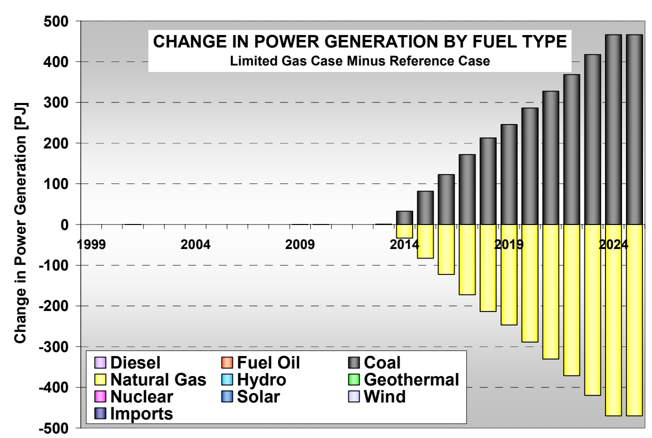

Figure 21: Limited Gas Scenario Change in Power Generation by Fuel Type

The lower gas generation noticeably slows the growth in total natural gas consumption. Gas consumption is expected to grow to 3,710 PJ, down from 4,678 PJ in the Reference Case. This reduction of 968 PJ or 21% is essentially because of reduced power sector gas demand as shown in Figure 22. Under the Reference Case, the power sector accounts for about 68% of total natural gas demand, but under the Limited Gas Scenario, this share is down to 53%.

In response to the reduction in gas demand for power generation, the need for new natural gas sources/imports declines. While approximately 2,690 PJ of gas has to be added/imported in the Reference Case by 2025, imports are down to 1,781 PJ under this scenario. As Figure 23 and Figure 24 show, the additional coal-fired generation cannot address the near- to intermediate-term natural gas needs. Additions/imports are substantially reduced only starting in 2014. The decrease of 909 PJ by 2025 is equivalent to a 34% reduction of natural gas imports.

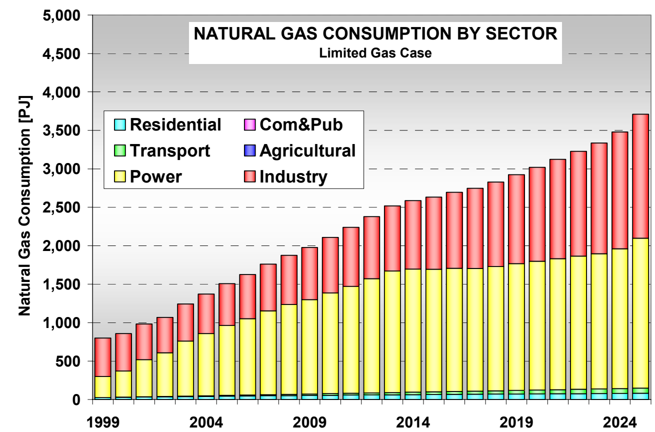

Figure 22: Limited Gas Scenario Natural Gas Consumption by Sector

At US$709.58 billion in net present value, the total economic system cost is higher than under the Reference Scenario; that is, a limitation on natural gas supply comes at an economic cost, in this case estimated to be an incremental cost of US$2.17 billion.

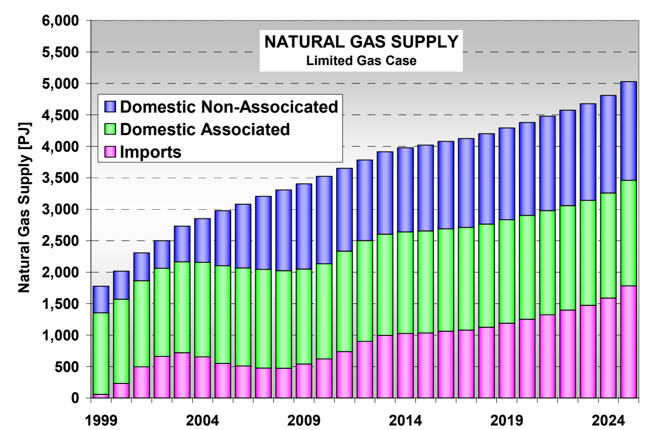

Figure 23: Limited Gas Scenario Natural Gas Supply

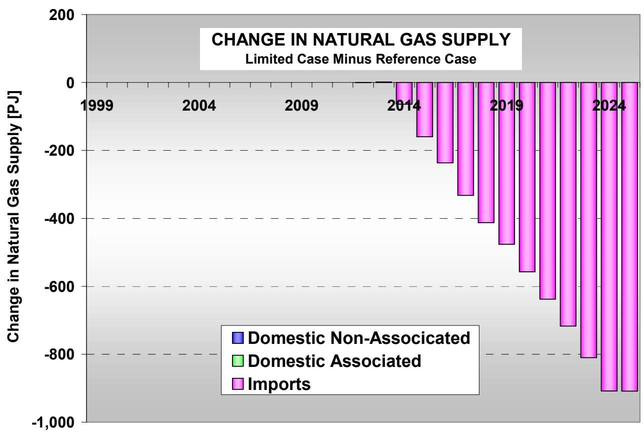

Figure 24: Limited Gas Scenario Change in Natural Gas Supply

Not surprisingly, the shift from gas to coal comes at an environmental cost as well. Atmospheric emissions are projected to increase under the Limited Gas Scenario. Figure 25 and Figure 26 show, for example, the changes in CO_2 and NO_X emissions compared to the Reference Case. Under the Limited Gas Scenario, power sector CO_2 emissions grow to 239 mt, while total national emissions reach 874 mt. This increase is about 46 million tons more than the Reference Case, equivalent to a 24% increase in power sector emissions, or 5.5% of national CO_2 emissions.

Emissions of NO_X exhibit a similar behavior in that power sector emissions are forecast to reach about 990 kt by 2025, which is about 152 kt, or 18%, higher than under the Reference Case.

Alternative Scenario Results – Other Scenarios

Detailed modeling results are also available for a renewables scenario and a nuclear power scenario. The renewables scenario shows the reduction in gas imports and atmospheric emissions associated with an accelerated introduction of renewable energy. The nuclear scenario presents similar types of results for a nuclear policy case that includes one additional nuclear unit. Please contact Guenter Conzelmann at guenter@anl.gov for information on the full set of scenarios.

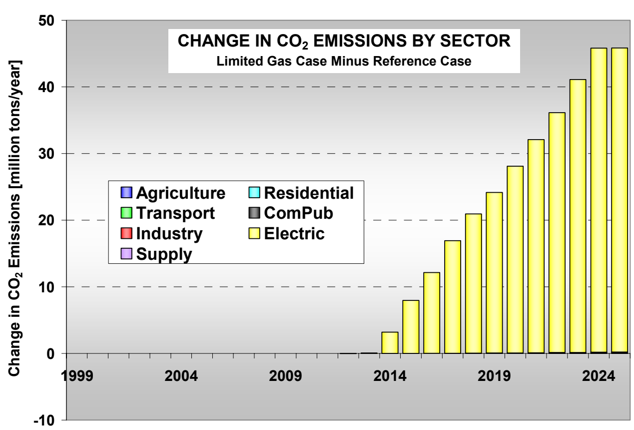

Figure 25: Limited Gas Scenario Change in CO_2 Emissions

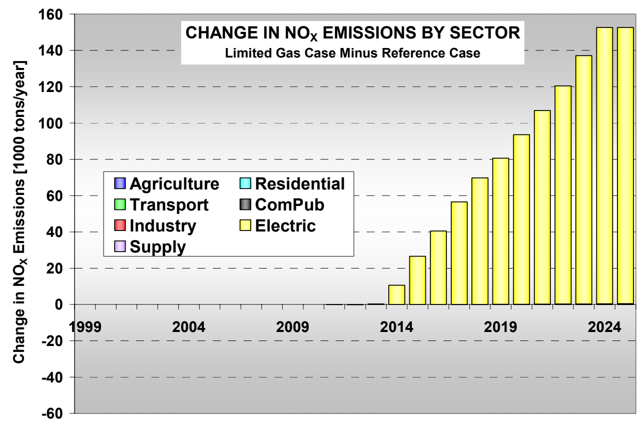

Figure 26: Limited Gas Scenario Change in NO_X Emissions

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